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CHARGE-PUMP ICs HELP PRODUCE SWITCHING POWER SUPPLIES THAT ARE CHEAP, EFFICIENT, SIMPLE, AND MUCH MORE "RF-FRIENDLY" THAN SUPPLIES THAT USE INDUCTORS. MANY VOLTAGE-CONVERTER ICs ARE AVAILABLE, AND CHOOSING THE RIGHT ONE IS NOT ALWAYS AS SIMPLE AS IT SEEMS.

The ins and outs of charge-pump-converter ICs

SWITCHED-CAPACITOR, OR CHARGE-PUMP, power supplies have existed for decades, but they have gained tremendous popularity in recent years, particularly in portable applications. These switching supplies and their converter ICs are popular because they convert dc voltages without using inductors. Although designers have made great progress in developing switching power supplies, inductors are still expensive, bulky, and prone to emitting RF energy. For low-power designs, a charge-pump topology is almost always preferable to an inductor-based approach when the charge pump's constraints and drawbacks—low power capability and limited output-voltage options—do not prevent the system from operating properly.

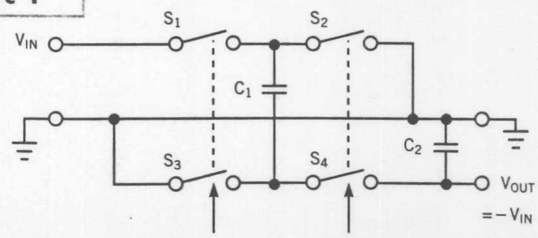
Charge-pump power converters operate by transferring the charge from one "flying" capacitor to another (**Figure 1**). When switches S_1 and S_3 are on, or closed, and switches S_2 and S_4 are off, or open, the input power supply charges C_1. During the next cycle, S_1 and S_3 are off, S_2 and S_4 are on, and charge transfers to C_2 with a change in polarity. The circuit in **Figure 1** represents the most popular application, a voltage inverter. This circuit is the best approach if you need to generate a voltage with the opposite polarity of the input. This circuit can also operate as a voltage doubler, if V − of the power supply floats off of ground.

Intersil's ICL7660 was the first charge-pump IC to contain all the functions necessary to perform voltage conversion. Many manufacturers, including Maxim Integrated Products (www.maxim-ic.com), Harris Semiconductor (www.harris.com), National Semiconductor (www.national.com), and the New Japan Radio Company (www.njr.com), still produce this generic IC. A number of ICs are available that use the same general principle but have different specifications and features. Choosing the right converter IC is not so trivial. A designer has to consider all the following factors when making a choice:

- input-voltage range,
- switching-frequency range,
- conversion efficiency,
- maximum output current,
- output resistance,
- quiescent current,
- shutdown mode, and
- price.

Input-voltage range appears to be one of the toughest parameters to specify when choosing the right converter. The design of most new converters tailors the ICs for operation with input voltages of 1.5 to 5.5V. If you need to convert 9, 12, or 15V inputs, your choices are limited. One of the most ba-

Figure 1



Charge-pump converters transfer charge from one "flying" capacitor, C_1, to another, C_2, by controlling the opening and closing of two pairs of switches, S_1/S_3 and S_2/S_4.

sic and inexpensive converters is the LTC1044 (Linear Technology Corp, www.linear.com). The data sheet states that 9.5V is the maximum input voltage for this IC. Thus, at first glance, it looks like you'd have no problem using this IC to convert a standard 9V output from a Type D battery to a −9V output from a "plug-into-the-wall" power supply.

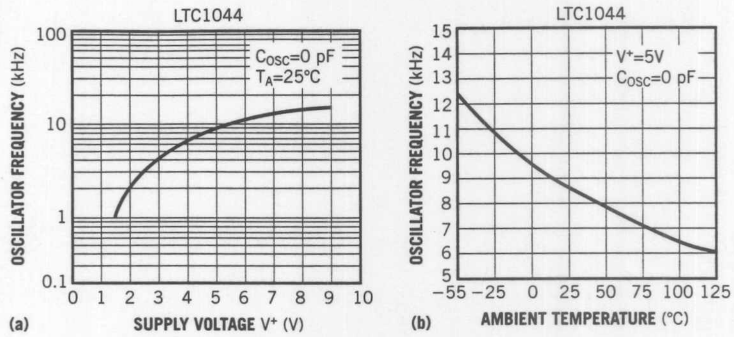
In reality, the design is more complicated. First, the output voltage of a fresh 9V battery can be as high as 9.6V with no load or a very small load. This situation is already dangerous to an LTC1044. Moreover, some batteries in this case size carry seven elements instead of six, so the output voltage could be more than 11V. Unfortunately, you have no way of knowing the number of elements except by measuring the output voltage with a multimeter, a step that most customers don't take. The LTC1044 can survive 9.6V, but the failure rate is statistically significant. However, when the input voltage nears 11V, all of the ICs blow. The same situation is true for wall plug-in power supplies.

You can never use an unregulated 9V power supply as the input to the LTC1044, even if you don't need regulation. The reason is that manufacturers rate their power supplies under full load, and the supply's input voltage is much higher if you use just a fraction of the rated load.

A more expensive regulated unit could solve this problem, but not without adding some troubles of its own. A regulator circuit needs some time—usually, a few milliseconds—to catch up with the input. During this period, the output voltage of the power supply equals the input minus some dropout, which often is sufficient to destroy the sensitive LTC1044 circuit. An input capacitor of 100 μF or more can fix this problem by creating in-rush charging current, which makes the transformer and rectifier sag.

So, what's the point of this long discussion when literally the next item on Linear Technology's list of inductorless dc/dc converters is a more robust 12V LTC1044A The answer requires a discussion of the next two items from the list of important IC factors: switching-frequency range and conversion efficiency.

Figure 2



Data-sheet curves for the LTC1044 show the effects of supply voltage (a) and temperature (b) on the oscillation frequency.

SWITCHING FREQUENCY AND EFFICIENCY

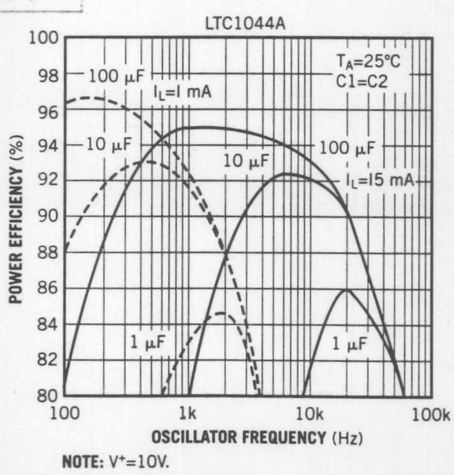
Many applications, such as audio and data-acquisition systems, are sensitive to residual ripple on power rails, so it is desirable to use high switching frequencies. Using high switching frequencies prevents these frequencies or their harmonics from interfering with signals. On the other hand, lowering the switching frequency can increase the efficiency to as much as 98% (**Reference 1**).

You can control the switching frequency of many converters by adding extra capacitors or jumpers between certain pins. In the LTC1044, connecting pins 1 and 8 boosts the switching frequency from 10 to 70 kHz, which is high enough for most audio applications. Conversely, adding external capacitors lowers the switching frequency. Also, you can drive or synchronize almost all converter ICs with an external clock. This feature is handy not only for increasing or decreasing the switching frequency, but also for helping to fight interference when powering up systems that use a dual-slope ADC. **Reference 2** includes an interesting example of driving the MAX1044 converter from an external 375-kHz square wave to power up radio circuits.

Switching frequency strongly depends on input voltage. The input voltage of the LTC1044 should not exceed 9.5V, but it can be as low as 1.5V. When the IC operates in standard mode (pins 1 and 7 disconnected), the frequency decreases to 1 kHz as the supply voltage decreases (**Figure 2a**). If you connect pins 1 and 8 to boost the frequency and if you don't want the frequency to be lower than 20 kHz, the input voltage should never go below 4 to 5V. Also, switching frequency changes with temperature (**Figure 2b**). Thus, if the output current is high, you must take into account the design's ambient temperature range in addition to the internal temperature of the IC. With a 100-mA output current, internal losses and the 60Ω minimum output resistance cause the LTC1044A to dissipate 700 mW. This amount of power not only requires some arrangements to remove the heat from most packages but also decreases the switching frequency.

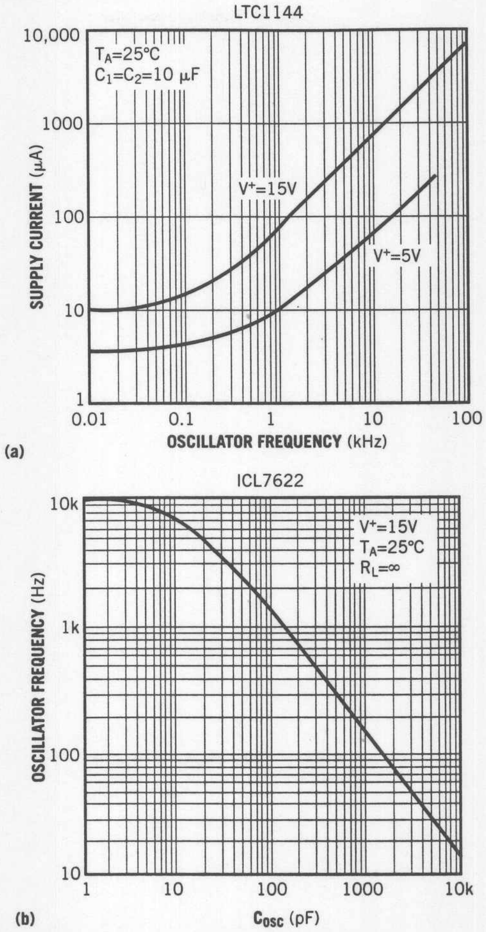
A simple example shows how to weigh the trade-offs among input

Figure 3



Data-sheet curves often don't define the design parameters you're interested in. For the LTC1044A, you have to extrapolate efficiency performance for output currents of 7 to 8 mA from these performance curves at 1 and 15 mA.

Figure 4



Weighing the trade-offs among input voltage, efficiency, switching frequency, and supply current is tougher than it seems. For the LTC1144, which is a higher voltage upgrade of the LTC1044A, supply current increases with frequency (a). You can also try the ICL7662 (b) in the pin-compatible LTC1044 socket, but a connection between pins 1 and 8 can prevent proper oscillation.

voltage, efficiency, switching frequency, and price. Say, for example, that you want to design a voltage inverter with a maximum V_{IN} of 9.5V, a switching frequency greater than 40 kHz, and a maximum output current of approximately 7 or 8 mA. Naturally, you want your inverter to be efficient, so you have to consider efficiency curves and quiescent current. Quiescent current may play a major role in defining overall efficiency in low-power applications of less than 10 mA and for applications that apply the load for only short periods or have long duty cycles. The data sheets for the LTC1044A indicate a maximum switching frequency of 100 kHz and a respectably low supply current of 200 µA. The data sheet also promises an efficiency as high as 98%.

Now, take a close look at **Figure 3**. For your desired combination of parameters, efficiency is so low that the data-sheet curves don't even define it. First, the curves in **Figure 3** apply only to 1- and 15-mA output currents. And even at 15 mA, which is approximately twice this design example's current requirement, efficiency is low. In practice, the efficiency will be less than 50% because the converter consumes about 9 mA when pins 1 and 8 connect to a 9V input. You have to significantly slow this chip to get reasonable efficiency of operation, at least under light-load conditions. The IC is simply too powerful; the large output-current capability results in low efficiency in low-power applications. You run into the same problem trying to use the LTC1144 chip, which is a higher voltage upgrade of the 1044A. Using the 1144, supply current increases with frequency (**Figure 4a**).

Other IC possibilities include the extended-input-range ICL7662 and Si7661 from Maxim Integrated Products. Although the ICL7662 allows input voltages as high as 20V, the data sheet doesn't clearly state the efficiency for a high switching frequency. However, because this chip is pin-compatible with the LTC1044, you can simply try it. Unfortunately, with pins 1 and 8 connected to increase frequency in the LTC1044 case, this ICL7662 may not work. Tying Pin 1 to Pin 8 disconnects the internal oscillator from the OSC Pin 7, and the IC oscillates only if a certain amount of parasitic capacitance exists (**Figure 4b**). Even after manually starting the oscillator (with your finger), the frequency is only 5 kHz. The last candidate from Maxim is the MAX1044. This IC's 10V maximum input voltage is close to the 9.5V maximum of the LTC1044. Thus, you face the same problems with the MAX1044 as you do with the LTC1044.

ADD INPUT PROTECTION

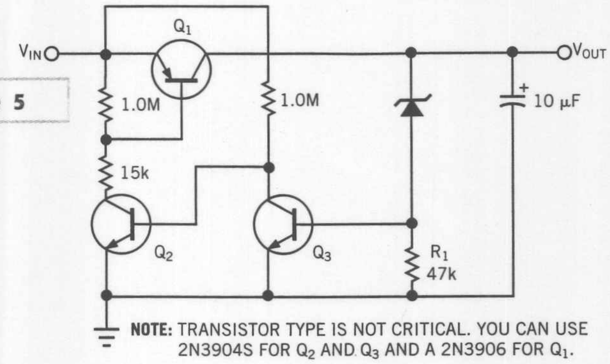
A simple LTC1044, which costs approximately $1 in large quantities, would be the best choice if only it could survive input voltage surges. If you have little extra room on your board, using this IC with some kind of protection circuitry is a viable option. Unfortunately, the most obvious and cost-effective way to implement input protection—using a zener diode with a resistor—is out of the question, because the usual value for voltage tolerances for zener diodes does not allow for efficiently protecting the input. In a worst-case scenario, this type of design wastes almost 1V of battery voltage on a ballast resistor. Only when battery voltage drops to 9.1×0.95=8.645V, which happens quickly because you are keeping the value of the resistor low, does the protector circuit stop consuming current. The result is a lot of wasted energy.

Another input-protection option is to use a low-dropout voltage regulator. Manufacturers offer a number of good low-dropout-regulator ICs. Unfortunately, most of these ICs are not low-power, such as less than 0.3 mA; not adjustable, which can be a problem because 9V is not a standard V_{OUT}; or simply too expensive. National Semiconductor's LP2951 is one of the few exceptions. This IC, which costs approximately 70 cents in large quantities, can provide 100 mA with a maximum dropout of 0.38V and a supply current of 75 µA.

Alternatively, a simple three-transistor regulator may provide the necessary input protection more cost-effectively than many ICs. The input and load regulations of the circuit in **Figure 5** are roughly fractions of 1%, which is more than enough for protection. The voltage drop is only about 200 mV with an output current of 10 mA, so the circuit does not reduce battery life. The same problem of the zener diode's tolerances exists, but, because this circuit consumes little current in regulation mode, the battery loses its juice much slower than in the resistor+zener case. Although you can adjust V_{OUT} by changing the value of R_1, this change affects regulation because the different Q points cause different zener-diode dynamic resistances. Varying regulation doesn't

matter much in this case, because the circuit is only for protection. However, V_{ZENER} and its temperature coefficient in this circuit differ from values presented on technical data sheets for zener diodes. This difference exists because the zener diode's current in **Figure 5** is small, to increase efficiency. You may need to experiment with the circuit to choose the right component values. This circuit costs pennies and allows you to use any battery and almost any power supply—even an unregulated one.

Figure 5



A simple three-transistor low-dropout regulator can provide input protection more cost-effectively than many ICs.

CONSIDER THE OTHER FACTORS

In addition to input voltage, efficiency, and switching frequency, important factors to consider when choosing a converter IC include maximum output current, output resistance, quiescent current, and shutdown modes. Output current is generally not a problem because you can find ICs, such as the MAX660, MAX665, MAX1680, MAX-1681 (Maxim Integrated Products), LTC1054, and LTC1144 (Linear Technology Corp), with currents as high as 100 mA. You can also use converters in parallel (**Figure 6a**). However, running two or more converters in parallel causes the ripple content to include not only individual switching frequencies, but also the difference frequency (**Reference 3**). The circuit in **Figure 6b** solves this problem by using the NOR gate to help synchronize the second 7660 with the oscillator of the first 7660 (**Reference 3**).

The other way to decrease output resistance and output ripple is to choose larger output capacitors. However, increasing the capacitance increases the turn-on time, which is crucial for certain applications. The best choice is to always use low-ESR components, such as ceramic or tantalum, for output capacitors.

Some converter ICs operate with higher switching frequencies than other ICs, such as 600 kHz for the LTC1516, 900 kHz for the LTC1550/1551, and as high as 2000 kHz for the LTC1429. For these ICs, you need to use an input capacitor to bypass the input power supply. This capacitor must sit as close as possible to the converter IC. This input capacitor provides most of the supply current while charging the flying capacitors of the charge pump. For high-frequency applications, this capacitor should be either ceramic or tantalum with at least a 0.1-μF ceramic capacitor in parallel. This input capacitor is unnecessary for low-frequency applications or when the output impedance of the power supply is low.

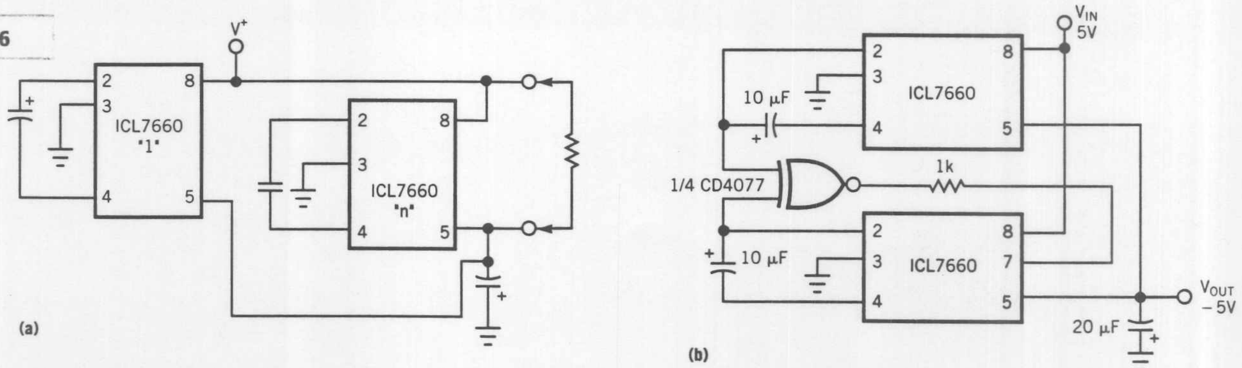
Large flying capacitors increase output ripple because they draw larger pulses of current from the input power supply. The big advantage of using larger flying capacitors is the ability to get better efficiency, particularly with lower frequencies (**Figure 3**), and the ability to provide larger output currents. Choosing the right value of the flying capacitors can be somewhat tricky because their values affect efficiency, output current, and output ripple.

When a more robust regulated output or extremely low output ripple is necessary, you probably need to use a low-dropout regulator. Again, the circuit in **Figure 5** works well for most cases. The LTC1054 and LTC1550/1551 (Linear Technology Corp) each include a built-in low-dropout regulator. The LTC1054 is pin-compatible with the 7660/1044 series and has a respectable input-voltage range of 3.5 to 15V, but it is more suitable for currents as high as 100 mA. The LTC1550 and LTC1551 are voltage inverters with a fixed −4.1V regulated output and hence less-than-1-mV output ripple. Maxim Integrated Products offers a number of converters with regulated outputs, mostly for biasing GaAs FETs.

FILTERING REMOVES OUTPUT RIPPLE

Filtering is another way to reduce output ripple. In the case of high switching

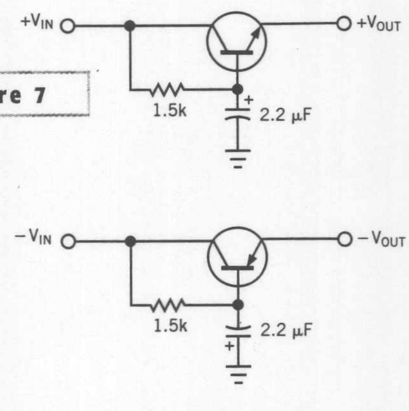
Figure 6



You can connect charge-pump converters in parallel (a) to increase output current, but this design increases the ripple. Using a NOR gate to synchronize the two ICs solves this problem (b).

frequencies, the filter can be a low-value RC or LC filter. Placing a ferrite bead in front of the output capacitor can also significantly improve output ripple. For lower frequencies, simple active-filter circuits can solve the problem for the price of a V_{BE} voltage drop (**Figure 7**). This filter is cheaper than a regulator circuit and consumes no current. If the main power supply has a high output impedance, which is the case for a battery, then you may need a filter at the power supply's output. Without an output filter, the converter IC's switching currents add ripple to the output voltage.

Figure 7



Simple active filters are often suitable for reducing ripple at low frequencies.

QUIESCENT CURRENT AND SHUTDOWN MODE

Some converters have very low quiescent current (60 μA for the LTC1514, 12 μA for the LTC1516, and 6 μA for the LTC1522 (Linear Technology Corp), so many cases need no shutdown mode. However, a shutdown option can be useful when the load has a long duty cycle. A powerful IC is necessary to handle heavy loads, and more powerful ICs have higher supply currents. In many portable applications, shutdown is the only way to conserve power. For a data-acquisition system, one way to implement the shutdown mode is to use the converter to supply power when the ADC is not in conversion mode and then to shut down the converter during the conversion cycle. This trick keeps power rails clean. However, capacitors need to provide enough energy storage for the ADC to ac-

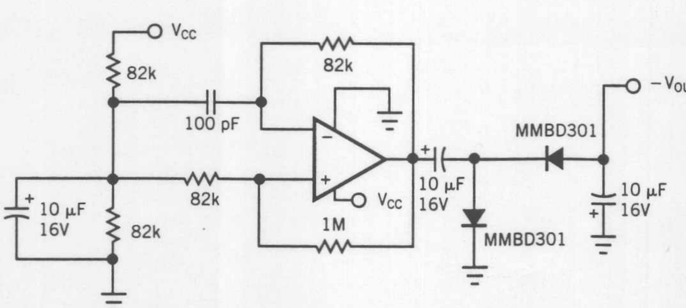
Not all converter ICs possess short-circuit protection, and some have only limited protection. The LTC1044 can continuously withstand a short circuit without damage but only for input voltages of less than 5.5V. Other ICs allow short-circuit conditions only for a certain time, such as 10 to 30 sec. As mentioned, heat dissipation can be a problem for high-current applications. You should consider this fact when choosing a package style and when laying out the pc board. Thick traces and copper areas can be helpful. Only a few converters, such as the LTC1514, LTC1516, and LTC1522, have the luxury of thermal protection. Such protection is uncommon, and manufacturers usually prominently advertise this feature.

Finally, you should consider the possibility that your design may not need a special converter circuit. The circuit in

of the circuit with a high or inverted voltage. All you need is an extra op amp or

clock signal. The values of the resistors and capacitors in the **figure** produce an oscillator frequency of approximately 25 kHz and keep current consumption low. For more efficient conversion, use rail-to-rail op amps and Schottky diodes. Theoretically, it's possible to multiply a voltage m or −m times, where m is an integer number. In practice, each additional stage increases the output resistance, and diode voltage drops also accumulate. Any circuit that can generate a pulse train with the desirable frequency is suitable for voltage conversion. Actually, you can use any alternative current waveform to perform conversion, particularly when the power requirement is small. In some cases, you can even use a system signal or some other signal, such as a local oscillator, to create an extra voltage source. □

Figure 8



If you need to power just a part of a circuit with a high or inverted voltage, you may not need a special converter IC. This simple converter circuit oscillates at 25 kHz to keep current consumption low.

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AUTHOR'S BIOGRAPHY

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